NASA TECHNICAL MEMORANDUM

NASA TM X-2167

NASA TM X-2167

PERFORMANCE CHARACTERISTICS OF IMPROVED SERVOAMPLIFIER FOR ELECTROHYDRAULIC CONTROL SYSTEMS

by Peter G. Batterton and John R. Zeller

Lewis Research Center
Cleveland, Ohio 44135

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • FEBRUARY 1971

1. Report No. NASA TM X-2167	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle PERFORMANCE CHARACTERISTICS OF IMPROVED SERVO-AMPLIFIER FOR ELECTROHYDRAULIC CONTROL SYSTEMS		5. Report Date February 1971
		6. Performing Organization Code
7. Author(s) Peter G. Batterton and John R. Zeller		8. Performing Organization Report No. E-5802
		10. Work Unit No. 720-03
9. Performing Organization Name and Address Lewis Research Center National Aeronautics and Space Administration Cleveland, Ohio 44135		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D. C. 20546		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

An improved servoamplifier has been designed which has the capability of driving low-impedance servovalve torque-motor coils. Frequency response data are provided showing the performance of the improved servoamplifier - torque-motor combination. To aid in analytical studies, a simplified dynamic model of the amplifier - torque-motor-coil combination has been included with data for three coil impedances. It is shown that an improvement of at least 2 to 1 can be obtained by using a 40-Ω/coil instead of a 200-Ω/coil servovalve. The printed circuit cards of the improved servoamplifier are completely compatible with the original hand-wired design.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Control systems Servoamplifier Electronic	Unclassified - unlimited

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price*
Unclassified	Unclassified	26	$3.00

*For sale by the National Technical Information Service, Springfield, Virginia 22151

PERFORMANCE CHARACTERISTICS OF IMPROVED SERVOAMPLIFIER FOR ELECTROHYDRAULIC CONTROL SYSTEMS

by Peter G. Batterton and John R. Zeller

Lewis Research Center

SUMMARY

For the past several years, fast-response (150 to 200 Hz) electrohydraulic servosystems have been used as research tools in experimental dynamics and controls studies. These systems normally include a fast-response electrohydraulic servovalve device that uses an electromagnetic torque motor as its initial stage. Included in these devices is a transistorized servoamplifier which provides the relatively high output impedance required by the servovalve torque motor to obtain the 150- to 200-hertz bandwidth.

Up to the present time, it has generally been felt that the 150- to 200-hertz bandwidth was sufficient. However, it appears that wider bandwidths will be required in the near future. One of the limiting factors in obtaining wide-bandwidth servosystems is the response of the servovalve to the servoamplifier. Thus, an improved version of the transistorized servoamplifier has been designed which has the capability of driving lower-impedance servovalve torque-motor coils. It is shown that an improvement of at least 2 to 1 can be obtained by using a 40-ohm-per-coil servovalve instead of the 200-ohm-per-coil servovalve.

To aid in analytical studies, a simplified dynamic model of the amplifier - torque-motor-coil combination has been included, with data for three coil impedances. The new printed circuit cards are completely compatible with the original hand-wired design, thus maintaining their flexibility. A single-card, printed circuit version of the original servoamplifier design is described in the appendix.

INTRODUCTION

Advanced propulsion system research continues to dictate a need for better high-performance servosystems. These servosystems are used both as actual components of the propulsion systems and as disturbance devices for studying the high-frequency dynamics of propulsion systems and their components.

An electrohydraulic servovalve and piston-in-cylinder actuator arrangement is normally selected to provide this fast-response (150 to 200 Hz) control capability. The basic closed-loop configuration for a servosystem of this type is shown in figure 1.

A typical servovalve employs an electromagnetic torque motor as the low-power control device for a higher power, one- or two-stage, hydraulic control-valve mechanism. The output flow of the servovalve responds to the torque motor output to frequencies in the range of 150 to 200 hertz. However, the torque motor responds to a low-impedance voltage input only to about 40 hertz. This limitation in the torque (or current) response of the torque motor is due to the equivalent inductance-to-resistance ratio (L/R) of the torque-motor coils. Thus the use of a high-output-impedance servoamplifier will improve the equivalent L/R and thus improve the response of the torque motor to the electrical input.

The servoamplifier design provided in reference 1 has generally fulfilled the requirements for the high-output-impedance electronic servoamplifier used in servosystems such as those described by figure 1. However, several circuit and packaging refinements can be made which further reduce the size and cost of the servoamplifier while at the same time improving the performance of the servoamplifier-servovalve combination.

This report discusses these refinements and provides more detailed information on the coil and drive circuit simplified dynamic representation (fig. 10 of ref. 1) for three different coil impedances.

Described in the appendix is a single-card, printed circuit design using the circuit components of reference 1. This design includes both a preamplifier stage and a power output stage on a single, printed circuit card for installations where this feature would be most convenient and where more than one preamplifier would not be required.

POWER OUTPUT MODULE

Description of Operation

The modified version of the fast-response coil drive circuitry developed in reference 1 is shown schematically in figure 2. This circuit employs a low-power, integrated circuit operational amplifier (OA1). The amplifier drives a complimentary pair (NPN-PNP) of silicon transistors (Q2 and Q3) in a push-pull mode. This particular push-pull stage of amplification separates the two servovalve coils. This is in contrast with the conventional parallel or series connections used with most single-ended servoamplifier schemes. By separating and essentially isolating the coils, the effect of the mutual inductance between the two coils is virtually eliminated. This shortens the time-constant of the coils. A detailed discussion of this circuit is provided in reference 1. Hence, only the modifications are discussed in detail in this report.

As in the original design, the power stage module includes a dither oscillator (Q1). The amplitude adjustable high-frequency (300 to 400 Hz) output is summed with the input to the amplifier stage and impressed on the torque-motor coils. This type of perturbation signal significantly reduces the stiction of moving elements in precision hydraulic control systems.

Circuit Changes

Two changes were made to the push-pull power output stage since the original circuit was designed. Improved output transistors were selected and some circuit components were eliminated. First, the MD985 complimentary pair output transistors were replaced by a 2N3904-2N3906 complimentary pair (Q2 and Q3). These transistors were chosen because of higher forward current transfer ratio and lower collector output admittance. Also, the cost of the 2N3904-2N3906 transistor pair is less than one-fifth that of the MD985. The forward current transfer ratio h_{fe} and the collector output admittance h_{oe} for these transistors are summarized as follows:

	2N3904-2N3906	MD985
h_{fe}	125	25
h_{oe}	5×10^{-5} mho	3.33×10^{-4} mho

(All symbols are defined in appendix A.)

By improving these transistor parameters, it should be possible to improve the performance of the power circuit module. For instance, the output impedance of the collector $1/h_{oe}$ helps make the transistor appear more like a true current source. Also, the increased current gain of the transistor will facilitate operation of this circuit at lower coil impedances by decreasing the output voltage requirements on the operational amplifier. For example, for output transistors with an h_{fe} of 25 and base drive resistors (R15) of 10 kilohms, 20 volts would be required of the operational amplifier to drive 50 milliamperes into the load. This is not possible with 15-volt amplifiers. For transistors with an h_{fe} of 125, only 4 volts would be required. Decreasing the base drive resistor (R15) could also decrease the voltage output required of the operational amplifier, but this may raise the load on the operational amplifier to unacceptable levels. The use of low-impedance servovalve torque-motor coils results in lower inductance-to-resistance ratios when using this power output stage scheme. This should improve the response of the torque-motor current to the amplifier output stage.

The second circuit change was to remove two diodes and one base drive resistor. Figure 3 is an abbreviated schematic of the original circuit showing these two diodes and the additional resistor. The function of the two diodes was to protect the transistors from excessive base-emitter reverse-bias voltage. Reverse biasing the base-emitter junction of the transistor with too much voltage may cause the transistor to fail. Since the base-emitter junctions of the transistors are essentially diodes, the bases of the two transistors were tied together as shown in figure 2. In this manner, the two transistors protect each other from possible excessive base-emitter reverse-bias voltage. As a result of tying the bases of the transistors together, only one base drive resistor is required to supply base current for the two transistors.

Other changes to the original circuit include replacing the 2N1671B unijunction transistor in the dither oscillator with a 2N4870 unijunction to reduce cost. Also, to lessen the space required on the circuit board, an integrated circuit operational amplifier was used instead of the plastic encapsulated discrete component version specified in the original circuit.

Component Selection and Package Configuration

The operational amplifier and transistors were chosen for the reasons mentioned in the preceding section. To simplify construction of these circuits, a printed circuit card was designed. Figure 4 shows this printed circuit card, both the foil side of the board and the component side with the components in place. The connector pins were arranged in the same manner as those of the original hand-wired cards so that it would be possible to interchange this new design with the old one. Table I is a complete parts list of the components required for three different servovalve coil impedances. The values of the current sensing resistor (R18) were chosen so that at full-rated current, the voltage drop across R18 is 1.25 volts. The values of R16 (and R17) were chosen so that 14.5 volts divided by the sum of the servovalve coil resistance plus R16 (or R17) plus R18 equals slightly more than full-rated servovalve coil current.

Dynamic and Steady-Stage Performance

The circuit shown in figure 2 has been used to drive two standard servovalves to determine the dynamic and steady-stage performance of this circuit-servovalve combination. The first servovalve had a rated coil resistance of 1000 ohms per coil. When the components suggested in table I were used, the full-power and quarter-power frequency responses shown in figure 5 were obtained. The full-power frequency response remained essentially flat to 90 hertz.

These frequency responses were obtained by measuring the voltage response across R18, the current sensing resistor. Since these data include the base drive current, these frequency responses appear somewhat better than they actually are. For the smaller values of R18 used with the lower servovalve coil impedances, this effect is reduced.

The second servovalve had a rated coil resistance of 200 ohms per coil and the circuit components suggested in table I were used. The full-power and quarter-power frequency responses at this resistance are shown in figure 6. With this coil resistance, the full-power frequency response remains essentially flat to 120 hertz.

A servovalve with a 40-ohm-per-coil resistance was not available for testing. However, a 40-ohm resistance and a 0.1-henry inductance were used to represent each coil and a full-power frequency response was taken. This response is shown in figure 7. Normally, servovalves of this coil resistance have inductances of around 0.15 henry, but quality inductors of these values were not available. Therefore, the response shown in figure 7 is actually about 50 percent better than would be expected for a 40-ohm-per-coil servovalve.

The steady-stage capabilities of this circuit are summarized as follows:

(1) Voltage-to-current gain, full rated/5 volts

(2) Input voltage offset, adjustable to zero

(3) Minimum coil resistance, 40 ohms

(4) Input impedance, 10 000 ohms

Simplified Block-Diagram Representation

This section should provide the controls analyst with sufficient information to model reasonably accurately the servoamplifier power output circuit for servocontrol system simulation and other studies.

In reference 1, a simplified block diagram of the power output module was presented. This block diagram is repeated herein as figure 8. The following equations are used to compute the values of the constants in the block diagram based on the values of the circuit components:

$$K_a = \left(\frac{R12}{R8}\right)\left(\frac{h_{fe}}{h_{oe}}\right)\left(\frac{1}{R15}\right) \tag{1}$$

$$K_{cf} = R18 \left(\frac{R8}{R11}\right) + \left(\frac{R8}{R12}\right)\left(\frac{R15}{h_{fe}}\right) \tag{2}$$

$$R_c = \text{Coil resistance} + R18 + R16 \text{ (or R17)} \tag{3}$$

$$\tau_c = \frac{\text{Coil inductance}}{R_c} \tag{4}$$

The values of these constants have been computed and are tabulated in table II along with other pertinent information for three servovalve coil impedances.

Using the values of K_a, K_{cf}, R_c, and τ_c, the block diagram of figure 8 was simulated on an analog computer. The resulting frequency responses are shown in figure 9 for the 1000-, 200-, and 40-ohm-per-coil servovalves. Both the full-power and quarter-power responses are shown on each figure. As expected, the response for the 1000-ohm simulation is not quite as good as the actual system since the base drive current is not included in the block-diagram simulation. However, there is good agreement for the 200-ohm-per-coil system. Although no real experimental data for a 40-ohm-per-coil system were available, it appears that the simulated data (fig. 9(c)) would be a fairly accurate representation of the expected response. By comparing figures 9(b) and (c), the frequency response obtained using the 40-ohm-per-coil data has at least twice the bandwidth of the 200-ohm-per-coil device.

PREAMPLIFIER MODULE

Circuit Description

A preamplifier module compatible with the power output module described in this report was also designed. The circuit diagram for this module is shown in figure 10. A parts list is given in table III. The foil pattern of the printed circuit card as well as the component layout is presented in figure 11. The design of this preamplifier is essentially the same as that used for the preamplifier described in reference 1 and is interchangeable with it. To save space, however, integrated circuit operational amplifiers were used instead of the plastic encapsulated discrete component types.

The preamplifier contains two operational amplifiers. The first amplifier provides high-impedance summing as well as variable gain. Three inputs (one variable) are provided for feedback, command, and a spare input channel. The second amplifier can be used to provide additional gain or for implementing servosystem stabilization (compensation) networks, or if not required, it can be deleted entirely. On the original card, the use of hand wiring facilitated the connection of various compensation networks. With a printed circuit card, however, there is a foil pattern to contend with. Thus, space was provided and the foil pattern configured for a "parallel T" network (R19 to R24 in figure 10) in the feedback path to the inverting input of the amplifier. Two additional spaces were provided at the noninverting input of the amplifier (R15 and R16) also. Figure 12 gives examples of two common compensation schemes that can be accomplished with the parallel-T network. These are a lead-lag and a lag-lead compensation. Many more compatible schemes could be wired in the space provided (ref. 2).

The unity-gain, full-power (20 V peak-to-peak) frequency response is flat to 4000 hertz where the outputs of the amplifiers start to rate-limit. This is a typical characteristic of this type of integrated circuit operational amplifier.

Packaging Criteria

Both the servoamplifier described in reference 1 and the improved version described in this report are packaged with the power output module on a separate circuit board from the summing and compensation amplifiers. For certain control applications, such as state variable feedback (refs. 3 to 4), there would be many feedbacks to the servoamplifier. Therefore, by keeping the preamplifier circuit separate from the power output circuit, as many preamplifier cards could be used as necessary to satisfy the control problem requirements.

For simpler control applications, it may be desirable to have all three stages packaged on the same circuit board. Since this was physically possible, a single-circuit-board configuration was also developed. A detailed discussion of this servoamplifier design is presented in appendix B.

CONCLUDING REMARKS

The servoamplifier circuits designed in reference 1 have been modified and improved so that they can be built conveniently on small, printed circuit cards and can provide the additional output capability for driving the low-impedance servovalve coils. The printed circuit cards simplify construction of the servoamplifier. The two-card version was designed to be compatible with the original hand-wired version of reference 1. For the three servovalve coil impedances studied, it was shown that the servovalve with the lowest coil impedance would have the capability of providing the best frequency response. This was made possible by the use of the improved output transistors. Finally, more data for the simplified block-diagram representation were provided for servosystem controls simulation studies using this servoamplifier. This method of representation continues to be reasonably accurate.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, October 1, 1970,
720-03.

APPENDIX A

SYMBOLS

C	capacitor, F
CR	rectifier
f	frequency, Hz
h_{fe}	forward current transfer ratio, A/A
h_{oe}	output admittance, mho
I	current, A
K	generalized gain
L	inductance, H
OA	operational amplifier
Q	transistor
R	resistance, Ω
s	Laplace variable
V	voltage, V
ZD	zener diode
τ	time-constant, sec

Subscripts:

a	amplifier
c	collector circuit
cf	current feedback
in	input

APPENDIX B

SINGLE-CARD PRINTED CIRCUIT CONFIGURATION

General Background

The servoamplifier circuit discussed in reference 1 was originally packaged on two separate hand-wired plug-in assemblies. To simplify the circuit assembly and to provide a more compact installation for multichannel applications, the original circuit design has been repackaged into a smaller configuration. In the modified version, the power and preamplifier stages of reference 1 have been combined on one common printed circuit board assembly. The following paragraphs briefly describe this new configuration. With this description, the circuit assembly can be considered for use in those installations in which a single plug-in card may more easily adapt than the separate cards discussed in the main portion of this report. This configuration is presently being used in some quantity at the Lewis Research Center for multiple-channel servosystems in our experimental facilities.

Circuit Assembly Description

The schematic diagram for the complete servoamplifier circuit is shown in figure 13. The parts list is given in table IV. An unassembled printed circuit board is shown in figures 14(a) and (b). An assembled board is shown in figure 15.

The single-circuit-card version uses the circuit and components of the original servoamplifier designed in reference 1. This came about because the single-card version was designed before the improved two-circuit-card design was available.

The schematic diagram of figure 13 shows the three major circuit functions that are now included on the single card: the power stage amplification, the dither oscillator, and the preamplifier circuit (first and second stage). From a circuit standpoint, these functions are identical to those of reference 1.

As discussed in reference 1, the second operational amplifier stage of the preamplifier is reserved for any required servoloop compensation. In the original hand-wired design, extra space was allotted on the preamplifier card for compensation circuit components. In keeping with this philosophy, the printed circuit card (fig. 14) has been designed with dummy components interconnected with the second preamplifier stage. This design is intended to provide for a diversity of compensation circuit configurations which might be necessary to meet various closed-loop system requirements.

REFERENCES

1. Zeller, John R.: Design and Analysis of a Modular Servoamplifier for Fast-Response Electrohydraulic Control Systems. NASA TN D-4898, 1968.

2. Jackson, Albert S.: Analog Computation. McGraw-Hill Book Co., Inc., 1960.

3. Schultz, Donald G.; and Melsa, James L.: State Functions and Linear Control Systems. McGraw-Hill Book Co., Inc., 1967.

4. Schultz, Donald G.: Control System Design by State Variable Feedback Techniques. Vol. 1. Arizona Univ. (NASA CR-77901), July 1966.

TABLE I. - POWER STAGE PARTS

<table>
<tr><th rowspan="3">Component designation</th><th rowspan="3">Description</th><th colspan="3">Servovalve coil type and rated current</th></tr>
<tr><th>1000 Ω
10 mA</th><th>200 Ω
25 mA</th><th>40 Ω
50 mA</th></tr>
<tr><th colspan="3">Characteristics</th></tr>
<tr><td>R1</td><td>Resistor, fixed</td><td colspan="3">10 kΩ, 1/2 W</td></tr>
<tr><td>R2</td><td>Resistor, fixed</td><td colspan="3">470 Ω, 1/2 W</td></tr>
<tr><td>R3</td><td>Resistor, fixed</td><td colspan="3">47 Ω, 1/2 W</td></tr>
<tr><td>R4</td><td>Resistor, variable</td><td colspan="3">50 kΩ</td></tr>
<tr><td>R5</td><td>Resistor, fixed</td><td colspan="3">50 kΩ, 1/2 W</td></tr>
<tr><td>R6</td><td>Resistor, variable</td><td colspan="3">50 kΩ</td></tr>
<tr><td>R7</td><td>Resistor, fixed</td><td colspan="3">50 kΩ, 1/2 W</td></tr>
<tr><td>R8</td><td></td><td colspan="3">10 kΩ, 1/2 W</td></tr>
<tr><td>R9</td><td></td><td colspan="3">1 MΩ, 1/2 W</td></tr>
<tr><td>R10</td><td></td><td colspan="3">75 kΩ, 1/2 W</td></tr>
<tr><td>R11</td><td></td><td colspan="3">2.5 kΩ, 1/2 W</td></tr>
<tr><td>R12</td><td></td><td colspan="3">500 kΩ, 1/2 W</td></tr>
<tr><td>R13</td><td></td><td colspan="3">1.5 kΩ, 1/4 W</td></tr>
<tr><td>R14</td><td></td><td colspan="3">2 kΩ, 1/2 W</td></tr>
<tr><td>R15</td><td></td><td colspan="3">10 kΩ, 1/2 W</td></tr>
<tr><td>R16</td><td></td><td>275 Ω, 1/2 W</td><td>300 Ω, 1/2 W</td><td>200 Ω, 1/2 W</td></tr>
<tr><td>R17</td><td></td><td>275 Ω, 1/2 W</td><td>300 Ω, 1/2 W</td><td>200 Ω, 1/2 W</td></tr>
<tr><td>R18</td><td></td><td>125 Ω, 1/2 W</td><td>50 Ω, 1/2 W</td><td>25 Ω, 1/2 W</td></tr>
<tr><td>R19</td><td></td><td colspan="3">25 kΩ, 1/2 W</td></tr>
<tr><td>C1</td><td>Capacitor</td><td colspan="3">0.01 μF</td></tr>
<tr><td>C2</td><td></td><td colspan="3">0.25 μF</td></tr>
<tr><td>C3</td><td></td><td colspan="3">0.005 μF</td></tr>
<tr><td>C4</td><td></td><td colspan="3">200 μμF</td></tr>
<tr><td>CR1,2</td><td colspan="4">Rectifier, silicon, 1N645</td></tr>
<tr><td>ZD1,2</td><td colspan="4">Zener diode, 1N4744A</td></tr>
<tr><td>Q1</td><td colspan="4">Unijunction transistor, 2N4870</td></tr>
<tr><td>Q2</td><td colspan="4">NPN transistor, 2N3904</td></tr>
<tr><td>Q3</td><td colspan="4">PNP transistor, 2N3906</td></tr>
<tr><td>OA1</td><td>Operational amplifier:</td><td colspan="3"></td></tr>
<tr><td></td><td>Open-loop gain</td><td colspan="3">15 000</td></tr>
<tr><td></td><td>Rated output</td><td colspan="3">±10V at 5 mA</td></tr>
<tr><td></td><td>Frequency response, unity gain</td><td colspan="3">100 kHz</td></tr>
<tr><td></td><td>Input voltage offset</td><td colspan="3">±7.5 mV</td></tr>
<tr><td></td><td>Input current offset</td><td colspan="3">±500 nA</td></tr>
<tr><td></td><td>Input bias current</td><td colspan="3">1.5 μA</td></tr>
<tr><td></td><td>Power supply</td><td colspan="3">±15 V dc</td></tr>
</table>

TABLE II. - CONSTANTS FOR SIMPLIFIED

BLOCK-DIAGRAM REPRESENTATION

Constant	Coil resistance, Ω		
	1000	200	40
	Coil inductance, H		
	4.0	0.8	0.15
	Full-rated current, mA		
	10	25	50
Collector circuit resistance, R_c, Ω	1400	550	265
Amplifier generalized gain, K_a, V/V	12 500	12 500	12 500
Current feedback generalized gain, K_{cf}, Ω	501.6	201.6	101.6
Collector circuit time-constant, τ_c, msec	2.86	1.45	0.566
$f_c\left(\frac{1}{2\pi\tau_c}\right)$, Hz	55.7	108	281

TABLE III. - PREAMPLIFIER PARTS

Component designation	Description	Characteristic
R1	Resistor, fixed	100 kΩ, 1/2 W
R2	Resistor, variable	50 kΩ
R3	Resistor, fixed	100 kΩ, 1/2 W
R4	Resistor, variable	50 kΩ
R5	Resistor, fixed	75 kΩ, 1/2 W
R6	↓	100 kΩ, 1/2 W
R7	↓	100 kΩ, 1/2 W
R8	↓	5 MΩ, 1/2 W
R9	↓	100 kΩ, 1/2 W
R10	↓	1 MΩ, 1/2 W
R11	Resistor, variable	10 kΩ
R12	Resistor, fixed	1.5 kΩ, 1/4 W
R13	↓	25 kΩ, 1/2 W
R14	↓	10 kΩ, 1/2 W
R15	↓	(a)
R16	↓	(a)
R17	↓	5 kΩ, 1/2 W
R18	↓	1.5 kΩ, 1/4 W
R19	↓	[a]10 kΩ, 1/2 W
R20	↓	(a)
R21	↓	(a)
R22	↓	(a)
R23	↓	(a)
R24	↓	(a)
C1, 3	Capacitor	0.005 μF
C2, 4	Capacitor	200 μμF
OA1	Operational amplifier:	
	Open-loop gain	15 000
	Rated output	±10 V at 5 mA
	Frequency response, unity gain	40 kHz
	Input voltage offset	±7.5 mV
	Input current offset	±2 nA
	Input bias current	11 mA
	Power supply	±15 V dc
OA2	Operational amplifier:	
	Open-loop gain	15 000
	Rated output	±10 V at 5 mA
	Frequency response, unity gain	100 kHz
	Input voltage offset	±7.5 mV
	Input current offset	±500 nA
	Input bias current	1.5 μA
	Power supply	±15 V dc

[a]Compensation components, unity gain inverter components are shown.

TABLE IV. - SINGLE-MODULE SERVOAMPLIFIER PARTS

Component designation	Description	Characteristic
R1, R2	Resistor, fixed	300 Ω, 1/2 W
R3		50 Ω, 1/2 W
R4, R5, R13		10 KΩ, 1/4 W
R6		22 KΩ, 1/4 W
R7		27 KΩ, 1/4 W
R9		470 KΩ, 1/4 W
R10		2.7 KΩ, 1/4 W
R11		10 KΩ, 1/2 W
R12		82 KΩ, 1/4 W
R14		470 Ω, 1/4 W
R15		47 Ω, 1/4 W
R16, R31	Resistor, variable	50 KΩ
R17, R18, R19	Resistor, fixed	(a)
R20		47 KΩ, 1/2 W
R21		25 KΩ, 1/2 W
R22		150 KΩ, 1/2 W
R23, R24, R25		(a)
R26	Resistor, variable	10 KΩ
R27	Resistor, fixed	1 KΩ, 1/2 W
R28		25 KΩ, 1/2 W
R30, R33, R34		100 KΩ, 1/2 W
R32		75 KΩ, 1/2 W
R29	Resistor, variable	200 KΩ
C1	Capacitor	0.25 μF
C2		750 μμF
C3		750 μμF
C4		0.01 μF
CR1, CR2	Rectifier, silicon, 1N645	
CR3, CR4	Rectifiers, silicon, 1N643A	
CR5, CR6		
CR7, CR8		
CR9, CR10		
CR11, CR12	Zener diode, 1N4744A	
Q1, Q2	Transistor, dual NPN-PNP, (MOT), MD985	
Q3	Unijunction transistor, 2N1671B	
OA1, OA2	Operational amplifier (Analog Devices), 108	
OA3	Operational amplifier (Analog Devices), 106	

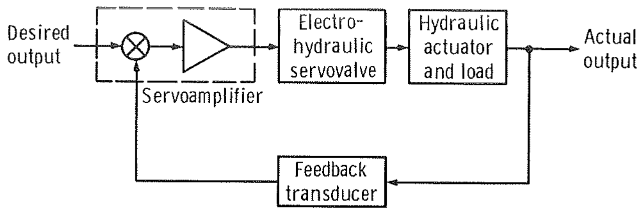


Figure 1. - Block diagram of electrohydraulic servosystem.

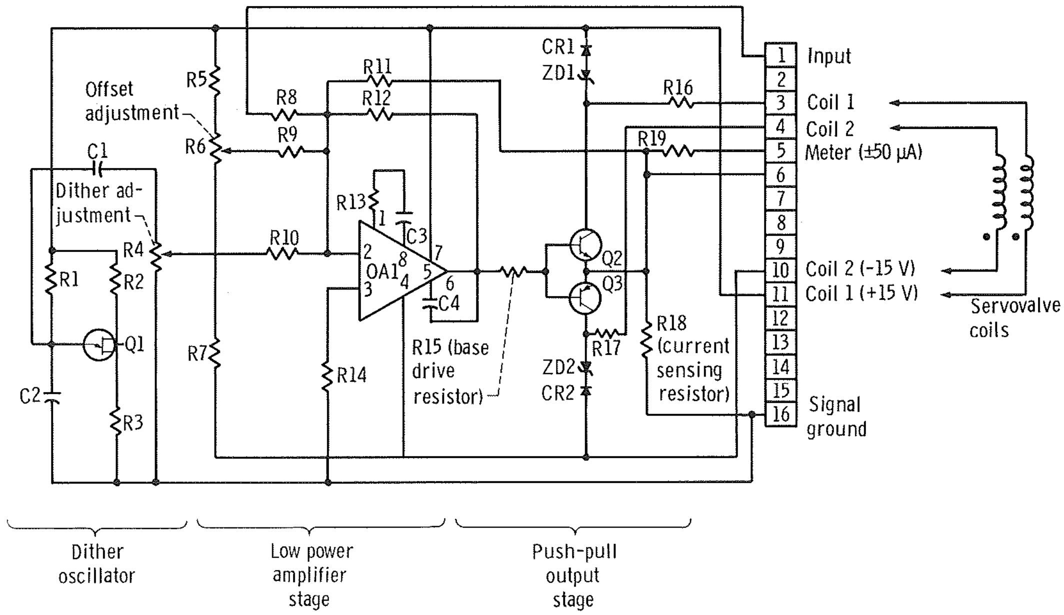


Figure 2. - Schematic diagram of revised power output module.

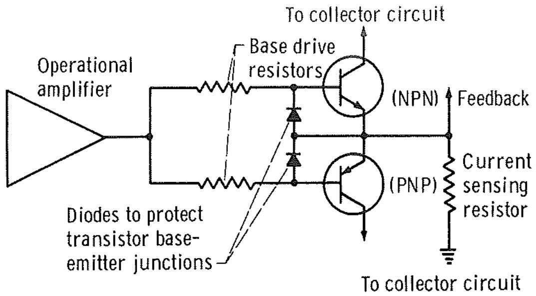
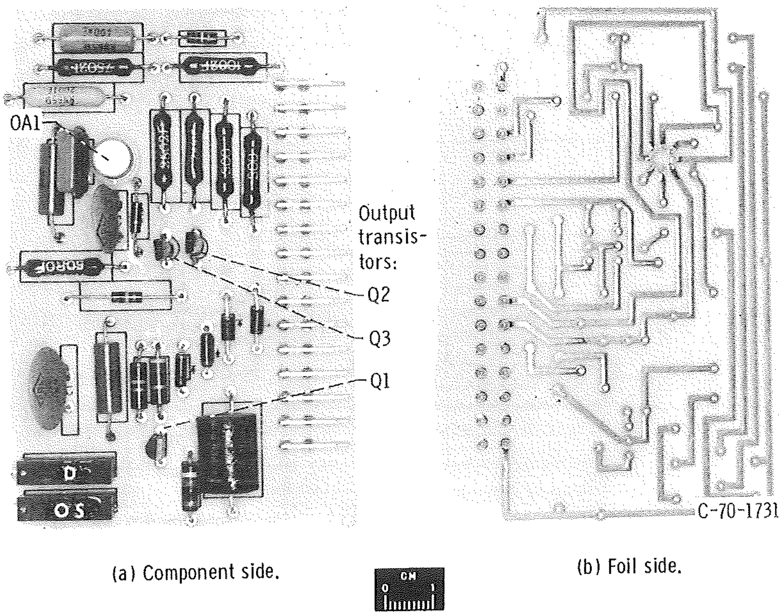


Figure 3. - Original base drive circuitry.



(a) Component side.

(b) Foil side.

Figure 4. - Power output module printed circuit card.

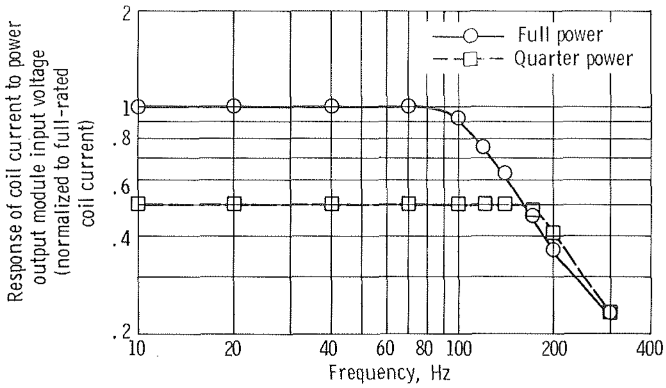


Figure 5. - Frequency response of servovalve coil current to power output module input voltage - 1000-ohm-per-coil servovalve.

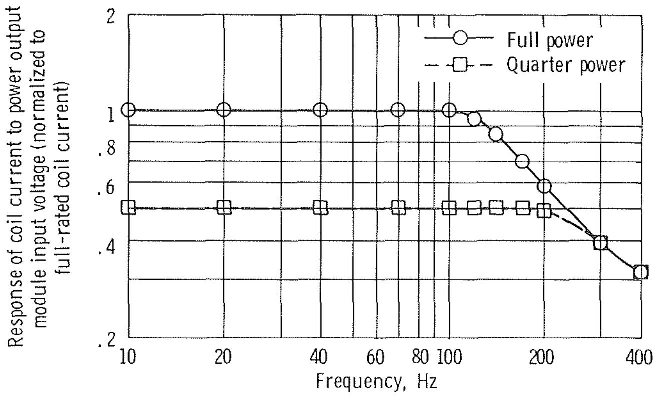


Figure 6. - Frequency response of servovalve coil current to power output module input voltage - 200-ohm-per-coil servovalve.

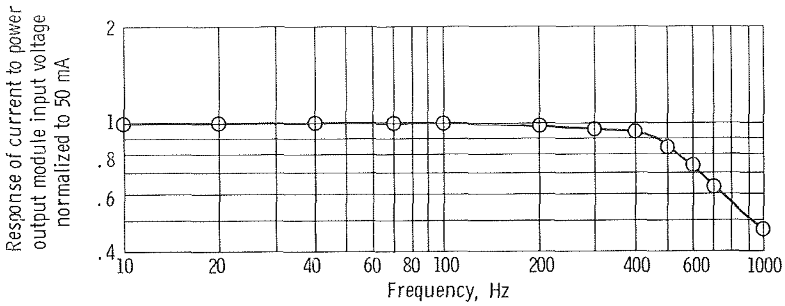


Figure 7. - Frequency response of current through simulated servovalve coil impedance of 40 ohms resistance and 0.1-henry inductance to power output module input voltage.

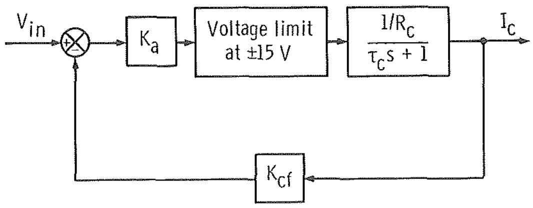
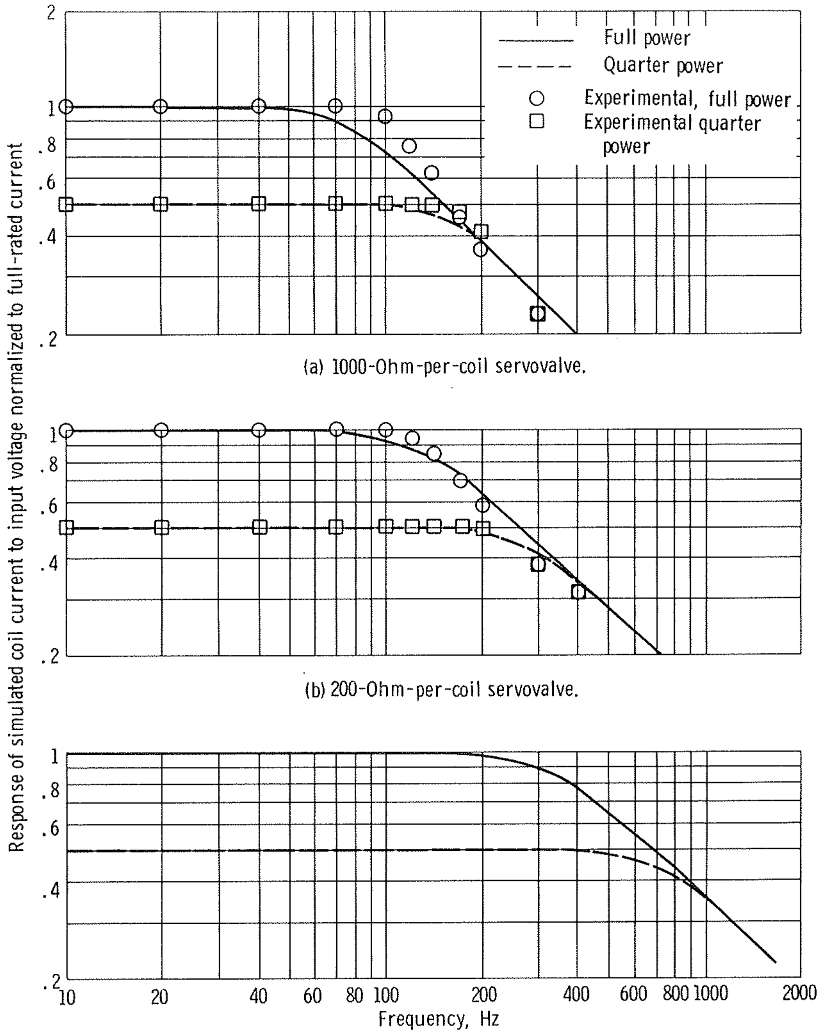


Figure 8. - Simplified block-diagram representation for dynamic analysis of power output module and servovalve.



(c) 40-Ohm-per coil servovalve.

Figure 9. - Frequency response of simplified block-diagram representation for 1000-, 200-, and 40-ohm-per-coil servovalves.

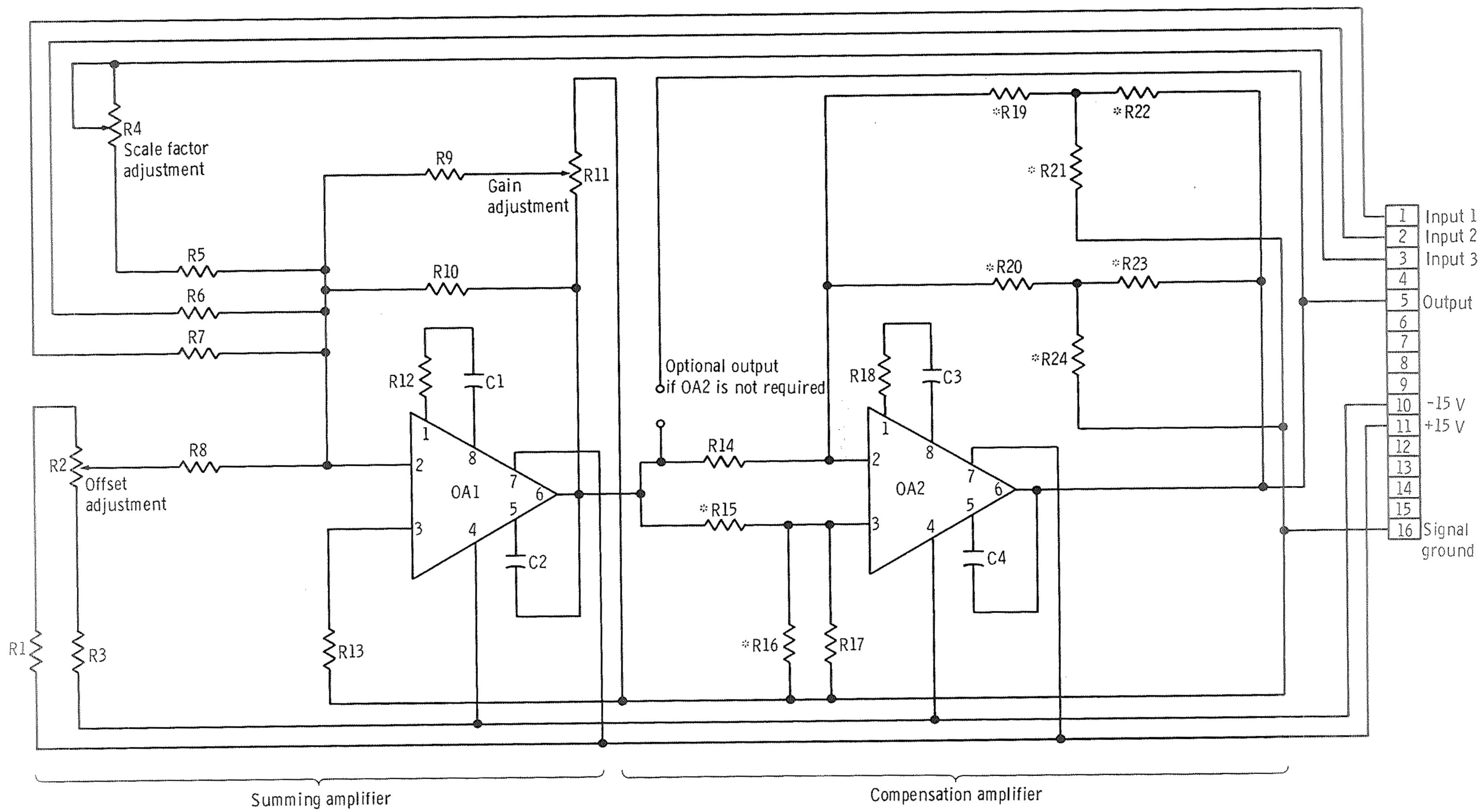
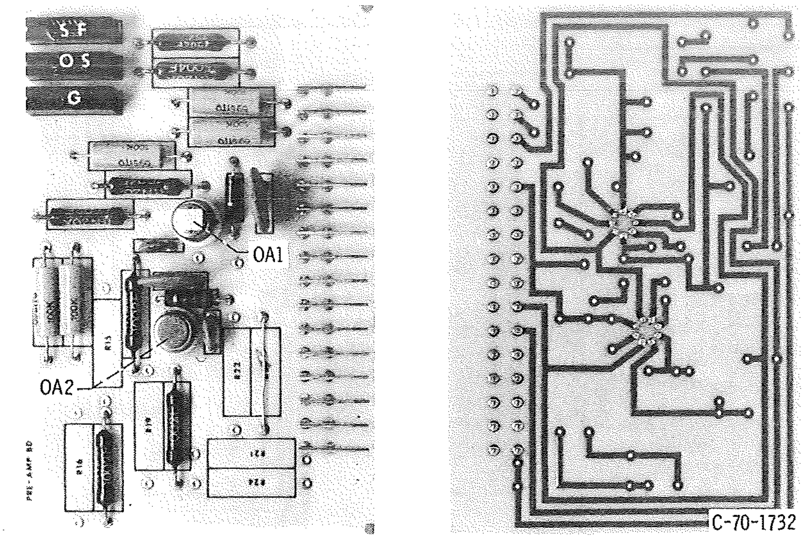


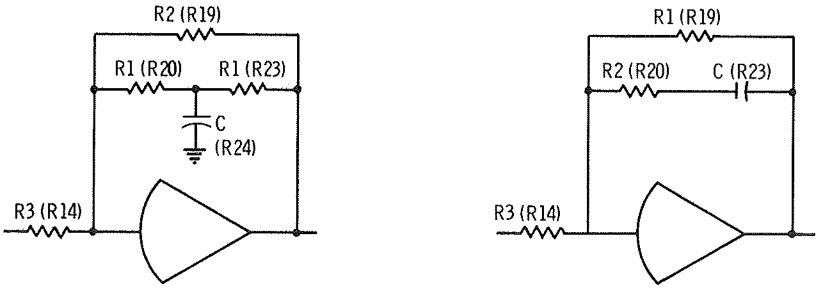
Figure 10. - Schematic diagram of preamplifier module. (Compensation component locations indicated by asterisk.)



(a) Component side.

(b) Foil side.

Figure 11. - Preamplifier module printed circuit card.



$$\frac{2R1R2}{R3(2R1 + R2)}\left(\frac{1 + \frac{R1C}{2}S}{1 + \frac{R1^2C}{2R1 + R2}S}\right)$$

(a) Lead-lag.

$$\frac{R1}{R3}\left(\frac{1 + R1CS)}{1 + (R1 + R2)CS}\right)$$

(b) Lag-lead.

Figure 12. - Example compensation schemes for preamplifier compensation amplifier. (Component locations are shown in fig. 10.)

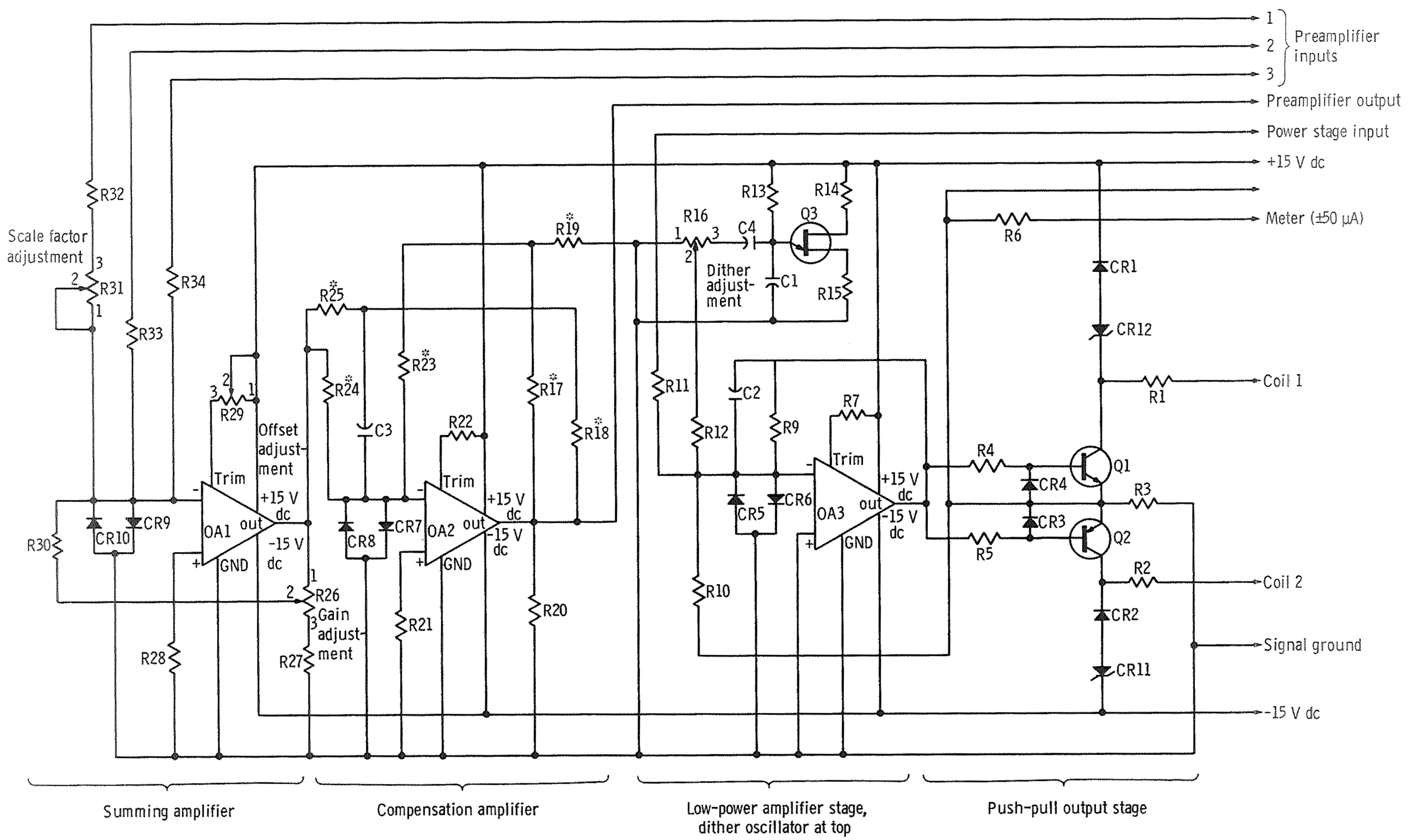
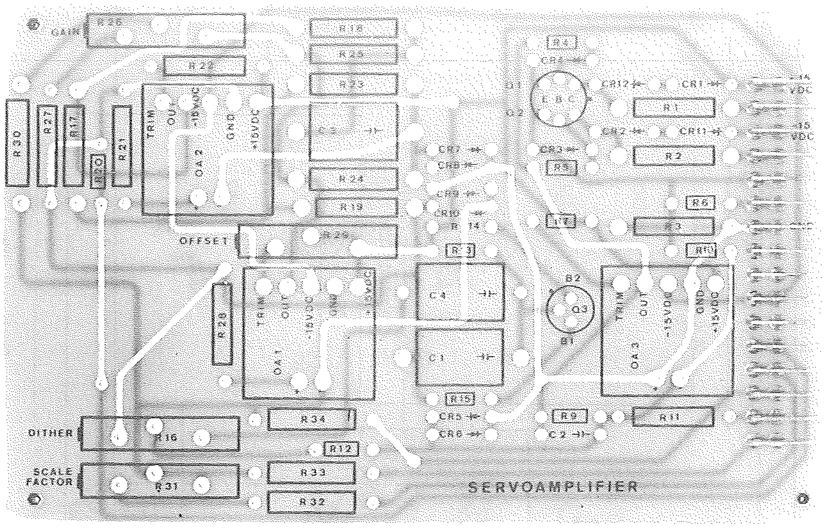
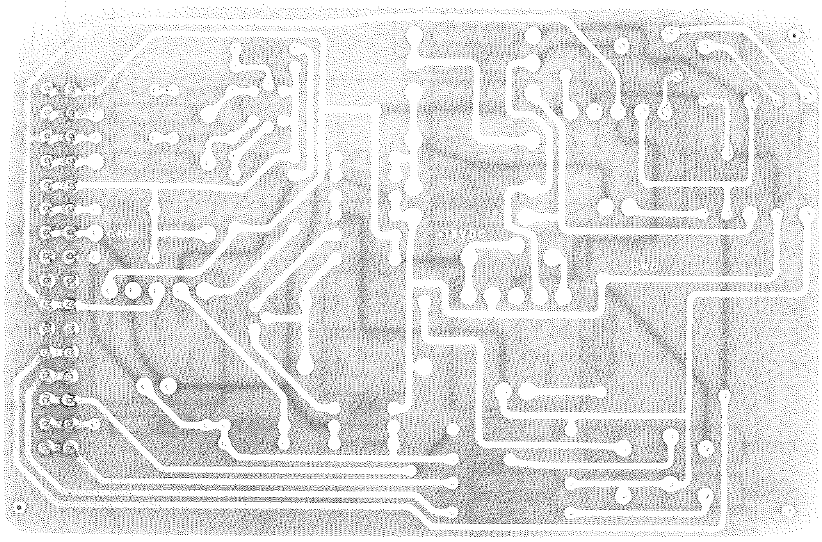


Figure 13. - Schematic diagram of single-card servoamplifier. (Compensation component locations indicated by asterisk.)



C-70-1729

(a) Component side of card.



C-70-1728

(b) Foil side of card.

Figure 14. - Unassembled single-card printed circuit servoamplifier.

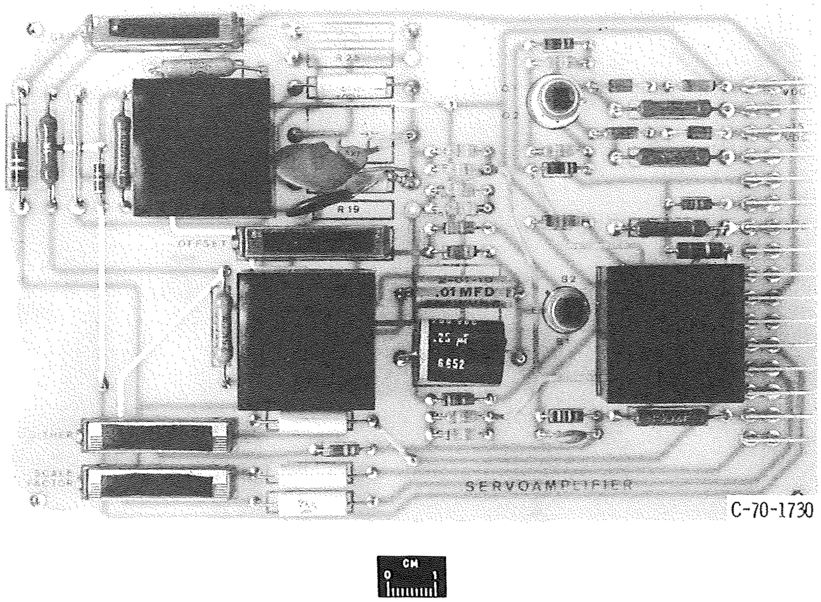


Figure 15. - Assembled single-card printed circuit servoamplifier.

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Scientific and technical information generated under a NASA contract or grant and considered an important contribution to existing knowledge.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

TECHNOLOGY UTILIZATION PUBLICATIONS: Information on technology used by NASA that may be of particular interest in commercial and other non-aerospace applications. Publications include Tech Briefs, Technology Utilization Reports and Technology Surveys.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION OFFICE

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546